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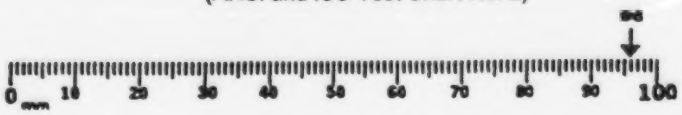

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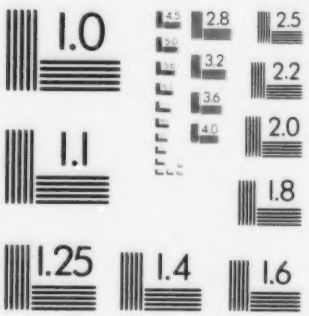

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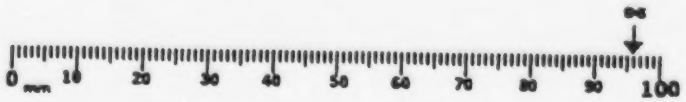

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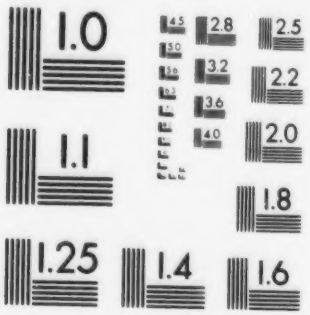

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RESEARCH REPORT

THE IMPACT OF URBAN FORM AND TRAVEL ACCESSIBILITY ON PRIVATE VEHICLE USE

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THE IMPACT OF URBAN FORM AND TRAVEL ACCESSIBILITY ON PRIVATE VEHICLE USE

SUMMARY

by
Hunt Analytics Incorporated

for
Susan Fisher, Research Division
Canada Mortgage and Housing Corporation

and

Environment Canada
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EXECUTIVE SUMMARY

Background

As awareness of the environmental impacts of private vehicle use grows, many researchers and policy makers have been seeking ways to reduce car use. There is a growing body of opinion that this can be achieved through careful design of the urban built form, including the encouragement of compact, mixed-use development patterns and improvements to transportation networks. But the degree to which such changes will result in reductions in automobile use is a source of debate. To make effective recommendations, it is important to have a thorough understanding of how land-use patterns affect car use. This study examines the factors influencing private automobile use by analyzing data on household travel behaviour collected in Edmonton.

In the following ways, this study fills significant gaps in our knowledge of the impact of urban form on vehicle use. These gaps were identified in a literature review conducted as part of this study.

- It uses empirical data on observed travel patterns in a Canadian city, resulting in conclusions that are more relevant for the Canadian context than previous empirical studies on this topic, which almost exclusively are based on data from other countries.

- It considers a wide range of measures that cover the complexity of influences on travel behaviour more completely than many previous studies. This includes mode-specific accessibility measures, which represent the spatial distribution of activities, involving both land use mix and density, and account for parking costs, transit fares, traffic flow rates and various components of travel times.

- It employs multiple-variable regression to take into account the effects of collinearity among the explanatory variables. Many previous studies have overestimated the influence of certain factors, such as density, because they considered only one explanatory variable at a time, thus failing to account for the correlation with other variables, such as household income and size.

- It considers a range of aspects of household travel behaviour, including mode choice, tour generation and number of stops per tour for both compulsory and discretionary travel, along with auto ownership, thus providing a more complete view of the full range of influences on different aspects of travel. This puts into perspective the results of previous studies that considered only one of these aspects, thereby establishing a more complete understanding of the influences of various factors on household travel and auto use in particular.

Method

Multiple-variable regression analyses were conducted to determine the influence of a range of explanatory variables on various indicator variables related to household travel behaviour, including in particular, the total vehicle kilometres travelled (VKT) by each household on a typical weekday. Data on travel behaviour were derived from a household travel survey conducted in the City of Edmonton, in which over 6,000 households reported their travel activities for the full 24-hours of a randomly assigned fall weekday in 1994. In addition to daily household VKT, the influences on household car ownership as well as compulsory and discretionary trips and tours were examined.

The explanatory variables include various representations of urban form along with household demographic characteristics, such as household income and size. Descriptions of urban form were developed by dividing the Edmonton census metropolitan area (CMA) into 486 zones,

each containing relatively homogenous urban form characteristics. The values for the variables (except demographic) assigned to each home and job location identified in the household survey correspond to the attributes of the zone in which they are located. Systems of nodes and links are used to represent the various networks of transport services, including the road network, the transit system, and walking and cycle paths.

The urban form variables fall into three categories:

- accessibilities measures for a given mode (i.e., automobiles, walking, cycling and transit) for zones containing the household and employment locations. Variables in this group concern the spatial distribution and magnitude of activities (a combination of density and land use mix) and the ease of travel between these activities as provided by the transport systems connecting them. A location's accessibility increases as the number of activities near it increases and as the utility of travel (ease, time, attractiveness and costs, including parking costs) to these activities increases;
- population and employment density; and
- neighbourhood road patterns.

Regression equations with various combinations of explanatory variables were estimated with the observed data, and indications of their influence on travel behaviour were derived.

Findings and Conclusions

Of all the different groups of variables examined (see methodology), the group of household demographic variables has the largest influence on auto use. Of all the variables studied, household auto ownership has the largest single influence. Other demographic variables, including household size and income, strongly influence the quantity of auto use. The strongest influences on automobile ownership are the number of people in the household, automobile accessibility for the home zone and household income.

Mode-specific accessibilities (measures that represent the proximity of activities, such as jobs and housing, and the ease and costs of travel between them) also have strong influences on household auto use. Making activities physically closer and increasing parking costs results in substantial reductions in daily household VKT. For example, a 50¢ increase in parking costs can result in a 3.4% reduction in VKT. Also by reducing walking times by 10% by making activities closer together, VKT can be reduced by 3.3%. As auto accessibility increases (i.e., easier and cheaper to travel by car), at both the home and work locations, households tend to own more automobiles and make much greater use of autos overall. As walk accessibility at the home location increases, households tend to own fewer autos and make less use of their autos overall.

The influences of accessibility measures on auto use are much greater than the influence of density on its own. Population and employment density variables can appear to have strong influences in regression equations concerning auto use when other variables, such as household income, which are correlated to density, are excluded. The apparent influence of density largely disappears when other correlated variables, in particular, mode-specific accessibilities, are included in the equations. This indicates that it is more appropriate to use mode-specific accessibilities than densities, since they capture the complex interplay between a wide range of factors, including proximity of activities. While density is a factor in the proximity of activities, it should be considered in combination with land use mix and other accessibility factors.

Household travel patterns are highly variable. Much of the variation in auto use is *not* explained by the set of factors considered explicitly in this study. The R^2_{adj} values for the various estimation runs did not exceed 0.33.

Road patterns have minor influences on auto use. Regular, rectangular street patterns tend to be associated with slightly less auto use than curvilinear street patterns. Access to transit also has a minor influence on auto use. As transit accessibility at the home location increases, households tend to own slightly fewer automobiles

and make somewhat less use of autos overall. Consistent with this, households located in zones without transit services tend to own more cars and make more use of autos overall.

In addition to daily household VKT, a variety of other aspects of household travel were considered, including number of tours, trips per tour, distance per trip and proportion of travel by auto for both discretionary and compulsory travel. The effects of certain factors on these different aspects were sometimes found to differ widely from their influences on daily household VKT. This shows that different indications can be found, depending on which indicator variables are examined. This helps to explain some of the apparently contradictory findings in previous studies that considered different subsets of the range of indicator variables.

Policy Implications of Findings

While this study shows that automobile use is largely influenced by factors beyond the 'reach' of planners and engineers, it also indicates that measures that improve walk, transit and bike accessibility and that reduce auto-accessibility can result in substantial reductions in household automobile use. The influence is greatest when these measures are applied in combination. Such measures include:

- reducing walk time by locating activities closer together, which could be achieved through intensification and mixed-use development;
- increasing parking charges;
- making walking and bicycling routes more direct;
- ensuring that street designs are more pedestrian-friendly, for example by providing attractive streetscaping, bus shelters, streets that are easy to cross, and pedestrian scaled spaces (e.g. buildings that are close to streets and small parking lots);
- introducing measures to slow down autos, such as traffic calming on existing streets and designing narrower roads in new communities;
- encouraging regular rectilinear street patterns over curvilinear patterns;
- reducing bus fares; and
- introducing bus priority measures in order to reduce bus running times.

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1. BACKGROUND

The private automobile provides Canadians with great personal mobility. But this mobility comes at a cost: private automobiles are a major source of pollutants that adversely affect human health and the environment. Despite advances in vehicle technology and cleaner fuels, harmful emissions are on the increase because, in Canada, the rate of car ownership and average vehicle size is increasing, as are the distances they are travelling (NRTEE, 1997). Negative impacts of the personal automobiles include:

- Greenhouse gas emissions: Private vehicles contribute significantly to CO_2 and other greenhouse gas emissions.
- Health impacts from ground-level air pollution: Cars are a major source of smog causing pollutants such as ground-level ozone and airborne particulates. Declining air quality is resulting in an estimated 1,800 premature deaths annually in Ontario (McPhail et al., 1998).
- Congestion: Traffic congestion causes stress, loss of productivity and inconvenience.
- Rising infrastructure costs: Governments face declining financial resources for maintaining and expanding roads. If current growth trends continue, the costs of maintaining and expanding roads may be prohibitively expensive.
- Loss of land: Land use for transportation infrastructure results in loss of land for wildlife habitat, recreation, agriculture and other uses.
- Water pollution: Storm-water runoff from roads causes water pollution.

Traditional solutions to the problem of vehicle emissions have concentrated on improving vehicle technology and fuel standards. Yet there is a growing body of opinion that the underlying need to travel by car must also be reduced and that this can be achieved through careful design of the urban built form, including the encouragement of compact, mixed-use development patterns and transportation networks that encourage alternative modes such as walking, cycling and transit. But this is a controversial topic, with some groups voicing concerns that the relationships between development patterns and automobile use in Canada are not well understood, and that proposed changes may do little to help the situation.

To make effective policy recommendations, it is important to have a thorough understanding of how land-use patterns affect car use and hence their contribution to greenhouse gas emissions and other negative impacts. To this end, Hunt Analytics Incorporated was commissioned by Canadian Mortgage and Housing Corporation (CMHC), in cooperation with Environment Canada and Health Canada, to study the factors influencing private automobile use in a Canadian context, using available data collected in the Edmonton region.

The objectives of this study were:

- to quantify the nature and strength of the influences of various aspects of urban form on private vehicle use by households in Edmonton; and
- to draw conclusions and make recommendations about future actions for Canadian cities in general.

2. STRUCTURE OF THIS REPORT

This report describes the study and discusses its results in terms of the nature of household auto use and the implications for policy intended to discourage auto use overall.

Chapter 3, is a brief review of the relevant literature, which is included to provide an appreciation of the nature of the current understanding of the issues involved and an understanding of the situation in Canada.

Chapter 4 is a description of the study method, indicating how the analysis followed an empirical approach with multiple-variable regression, the sources of the observations of household travel behaviour used, the specific indicator and explanatory variables considered, the statistical estimation approach employed and the development of indications from the estimation results.

Chapter 5 presents some of the estimation results and considers the findings arising from them, particularly those concerning the overall goodness-of-fit, the effects on the quantity of private vehicle use and on household auto ownership, including the effects of various specific elements of urban form and the nature of household travel behaviour generally.

Chapter 6 compares the results of this study with those of another similar study, with the close similarities in comparable results adding to the credence of the results obtained here. Chapter 7 considers some of the policy implications of the results obtained here. Chapter 8 offers conclusions, including a summary of the main findings, a summary of the policy implications of the findings, an indication of the potential limitations of the work done and the corresponding implications regarding the results, and a discussion of appropriate directions for further work.

3. LITERATURE REVIEW

This section highlights the major findings arising from the literature review and outlines the conclusions to be drawn with regard to this study.

Indications from Literature Review

There is debate over the nature and strength of the influence of urban form on car use.
The overriding opinion in the literature is that urban land-use planning can influence automobile use by reducing trip distances and encouraging the use of alternate modes. The key issue is not whether urban form affects private vehicle use, but rather whether the effect is strong enough to contribute substantially to efforts to improve air quality and provide the other social and environmental benefits associated with reduced automobile use. The nature and strength of the influences on car use are the subjects of ongoing debate. While the literature in this area is vast and growing rapidly, thorough empirical research providing definitive indications of the relative strength of these influences has been severely limited.

The use of multiple-variable regression analysis to indicate the relative strength of influences has been limited.
One of the most frequently cited studies linking urban form with car use is by Newman and Kenworthy (1989a, 1989b). It compared the per capita gasoline use of 32 cities around the world. The cities with the highest gas consumption, such as Houston and Phoenix, are also the least densely populated, while those with lowest gas consumption, such as Hong Kong and Tokyo, are the most dense. Newman and Kenworthy concluded that gas prices, income and vehicle efficiency accounted for about 40 per cent of the variance, and that most of the remaining variation was explained by urban population density. They concluded that density was the single most important explanatory variable. Cervero (1989), Holtzclaw (1990) and Dunphy and Fisher, (1994) have also found strong correlations between density and car use. Critics of Newman and Kenworthy's approach, such as Gomez-Ibanez (1991), Giuliano and Small (1993), Brindle (1994) and Schimek (1996) noted that their statistical model failed to account for the correlation between density and other variables, such as household income, thereby seriously underestimating the influences of these other variables while overestimating the influence of density.

Newman and Kenworthy's approach relied on single variable comparisons where only one explanatory variable and one indicator variable are considered at a time. This approach does not determine the relative strengths of the influences of these variables compared to others. Moreover, if the explanatory variable is correlated with other unconsidered variables, the strength of the influence of the considered variables appears to be greater than it really is. In particular, as noted by the critics of this approach, when density is considered by itself, its correlation to household income and smaller household size is not accounted for, thus overestimating its explanatory power.

An approach that enables comparisons of the relative strength of explanatory variables and alleviates collinearity problems with unconsidered variables is multiple-variable regression analysis. In this approach, an indicator variable is regressed against sets of any number of explanatory variables. Theories regarding the influences of variables or groups of variables can be tested using different combinations of explanatory variables. Examples of studies of the influence of urban form on car use that use multiple regression include:

- Cervero and Gorham (1995) controlled for variations in income, transit service and distance from the central business district (CBD) in a comparison of work trip travel characteristics of an older, compact, mixed-use neighbourhood and a newer, spread-out, auto-oriented neighbourhood in both San Francisco

and Los Angeles. The use of transit, walking and cycling for work trips was found to be higher in older, compact neighbourhoods.

- Ewing (1995) examined travel characteristics for all trips in 548 Florida households. Independent variables include household size, income, housing type, auto ownership, residential and employment density, jobs/housing balance and proximity measures. While zonal densities and jobs/housing balance on their own had significant inverse relationships to car use, when the influences of demographic variables was controlled, the influence of density became weak, paling beside the influence of proximity to activities at a region-wide level.

- Frank (1994) investigated the impact of mixed-use and density (population and employment) on car use, transit and walking in Puget Sound households. Car use was consistently found to be negatively related to density and land use mix.

- Giuliano and Small (1993) determined that jobs/housing balance did not have a large influence on commute times in Los Angeles.

- Kitamura et al. (1994) analyzed land use and travel patterns in five neighbourhoods in San Francisco. While demographic and neighbourhood variables offered significant explanatory power, attitudinal variables explained the highest proportion of variation in the data.

- Patterson et al. (1993) conducted one of the few multiple regression studies using Canadian data. They studied annual transit ridership per capita in 12 Canadian cities. The most significant explanatory variables were transit vehicle hours of service per capita and urban area density, with a positive relationship between transit use and density.

- Schimek (1996) studied the effect of density on car ownership and use in a national survey in the United States, accounting for the correlation between density and income. The most important determinants of ownership were found to be household income, size and number of workers. Population density had only a small impact on vehicle ownership, after controlling for these other factors. Each one per cent increase in household income resulted in a 0.32 per cent increase in vehicle kilometres travelled (VKT) while each one per cent increase in population density resulted in a 0.07 per cent decrease in VKT.

More empirical studies is needed in the Canadian context.

Empirical research indicating the relative strength of these influences is particularly lacking in the Canadian context. Surveys of travel behaviour are available for most major Canadian census metropolitan areas (CMAs) and, in some cases, analyses of the impacts of urban form and locational characteristics on car use have been conducted, for example in the Greater Toronto Area (Gilbert, 1995; IBI and Stephen McLaughlin Consultants, 1990), the Regional Municipality of Ottawa-Carleton (IBI, 1993) and national comparisons of Canadian cities (Angus Reid Group, 1991; TAC, 1996). Among other conclusions, these show that those living in denser, more central areas have lower rates of car use. In the Ottawa-Carleton example, automobile usage was found to be influenced by residential densities, employment densities, personal vehicle availability, level of transit service and household income.

The topic has generated considerable interest and a wide range of indications of influences.

The literature review revealed a vast body of information on the influence of urban form on travel patterns, although most do not point to definitive indications of the strength of the influence. The wealth of material is an indication of the level of interest and debate it has sparked. There have been several published literature reviews on the subject including Berman (1996), Giuliano (1989), Handy (1992b), PBQD (1996), Steiner (1994), Banister (1992) and Anderson et al. (1996).

In the literature of empirical studies, the range of variables studied is also vast. These include:

- categories of travel (compulsory trips only, discretionary trips only, all trips);
- levels of data aggregation (individual traveller, individual household, neighbourhood/ transport analysis zone, cities/urban regions);
- indicator variables (number of trips, vehicle kilometres travelled, gasoline or energy consumption, modal split, time spent community); and
- explanatory variables including socioeconomic characteristics (e.g., household income, number of residents, age, automobile ownership), neighbourhood form (e.g., population density, employment density, jobs-to-housing ratio, local retail availability, street pattern, level of transit service, road length per unit area, parking conditions, sidewalk provision) and city form (e.g., distance to nearest commercial centre, CBD size, gross employment density). Some studies mix socioeconomic and urban form explanatory variables to determine the relative explanations, such as Kitamura et al (1994), Frank (1994), Frank and Pivo (1994), Handy (1993), Hunt (1995) and Schimek (1996).

The literature also reveals interest in how specific development trends can reduce car use. With regard to neo-traditional communities, Crane (1996a, 1996b) and Berman (1996) have observed that the empirical support for the claimed transportation benefits of the new urbanism concept is meagre. Studies of actual neo-traditional developments have yet to be published as virtually none is fully built at this time. Questions over the link between car use and the presence of sufficient land use mix (e.g., shopping) and employment opportunities and whether residents would use these destinations in their own neighbourhood remain at the theoretical level.

Accessibility measures are rarely considered. The accessibility of a location is a numerical measure of the location's proximity to activities. Various forms of accessibility measure have been developed, taking into account both the number of activities and the relative ease of travel to them from a given location, including both the money cost and time spent on each component of the journeys involved. As such, these measures incorporate representation of the spatial distributions and patterns of activities, the associated densities of these activities and the quality of service provided by the transportation system. They are intended to provide an indication of the human perception of space and the distribution of activities, and resulting travel needs that arise, and they are used extensively in urban travel demand analysis and modelling.

As discussed above, the linkages between travel and urban form, transportation network supply and demographic factors are complex, and it is difficult to differentiate cause and effect. It has been shown that higher residential density is correlated with lower incomes, lower car ownership, smaller household size, increased transit services and higher accessibility to destinations. Very few studies distinguish among these complex factors to determine the influence on car use. Accessibility measures have been considered only a few times, which is somewhat surprising given their clear applicability. Even more surprisingly, it would appear that no studies have considered mode-specific accessibilities, which indicate the ease of travel for particular modes, such as car or transit, rather than all modes altogether.

Handy (1992a, 1992c, 1995, 1996) examined the influence of urban form and discretionary travel, particularly shopping trips, by comparing two compact, mixed-use traditional and two dispersed, suburban neighbourhoods in San Francisco. Both accessibility within the neighbourhood and the region were considered. The findings showed that higher accessibility, in terms of shorter distances to destinations and qualitative factors, lead to a greater number of walking trips. The accessibility of the residential zone was found to affect the miles travelled for shopping trips, rather than the number of trips.

Conclusions from Literature Review

This review of the literature permits a few observations about the influences on private auto use.

- Income and age influence travel patterns. Auto ownership also displays an influence on travel.

- Higher population and employment densities correlate with lower quantities of auto use. But the range of other influences that should be considered along with these density measures is complex, so it is difficult to see if they are acting as surrogates for other influences, such as household income. Studies involving multiple regression and a wide range of explanatory variables alleviate these collinearity problems, with results indicating that density has less influence than has been concluded in other studies.

- The mix of land uses, while not often considered, has been found to have some influence on travel patterns.

- Higher walk accessibility, in terms of shorter distances to destination and qualitative factors, correlate with higher quantities of walking trips.

- Better transit service provision is linked with increased transit use.

This review also indicates that further research should:

- use data from a Canadian context;
- be empirical, based on observed travel patterns;
- consider a wide range of measures that covers more completely the range and complexity of influences on behaviour, including mode-specific accessibility measures that represent the spatial distribution of activities (involving both land use mix and density) and take account of parking costs, transit fares, traffic flow rates and so on, from a traveller perspective; and
- employ multiple-variable regression to eliminate collinearity between explanatory variables.

Accordingly, the research reported here does all of these.

4. METHOD

Overall Analysis Approach

The basic approach used in the analysis is to estimate a system of regression equations concerning the influence of various factors on household travel behaviour. The dependent (indicator) variables used in this study are derived from data on household travel behaviour collected in Edmonton, Alberta, such as the average trip distance and proportion of travel by auto. The key dependent variable is the total private vehicle kilometres travelled (VKT) by a household over a 24-hour period.

The explanatory variables used in the regression analysis include various representations of urban form and household socioeconomic (demographic) characteristics. The resulting estimation results and related statistics provide indications of the influences of the specific explanatory variables and groups of explanatory variables on private vehicle use.
A sensitivity analysis was conducted concerning a specific set of variables in order to provide further indications of the influences of certain factors.

Data Sources

Observations of household travel behaviour are derived from the City of Edmonton Household Travel Survey, in which over 6,000 households from a range of locations in the Edmonton CMA reported their travel behaviour for a 24-hour randomly selected weekday in the fall of 1994. The survey involved approximately 12,100 people and 62,500 trips. Each observation concerns an individual household.

The City of Edmonton commissioned this survey to use in the development of a computer model of travel behaviour in the Edmonton region called the Edmonton Transport Analysis (ETA) Model (Hunt et al., 1998). The ETA is designed to represent all person travel in the Edmonton CMA over the 24 hours of a typical weekday. The entire Edmonton CMA is divided into 486 geographical units called ETA zones. These zones act as the locations of residential and employment activities and the origins and destinations of trips. Systems of nodes and links are used to represent the various networks of transport services in Edmonton, including the road network, the transit system, and walking and cycle paths. Volumes of travel demand are loaded onto these networks and the resulting congested flows are used to determine the times and costs for travel between zones.

The information on relevant aspects of urban form is developed using the ETA Model and various other descriptions of conditions in Edmonton. The travel times and costs used in the analysis are those used in the ETA Model for the calibrated simulation of conditions at the time of the Household Travel Survey. Similarly, the employment, population and dwelling unit totals and densities used in the analysis were developed using the corresponding values for the ETA zones. These values were themselves developed from various City of Edmonton data bases and Statistics Canada estimates (City of Edmonton, 1997a).

Indicator Variables

The system of equations for the vehicle kilometres travelled (VKT) indicator variable has the following general form:

$$\begin{aligned} VKT &= AUKMC + AUKMD \\ &= TOURC * CATTC * CADTC * CPDAC \\ &\quad + TOURD * CATTD * CADTD * CPDAD \end{aligned}$$

where:

AUKMC = total distance all autos are driven by all household members as part of *compulsory* tours, in kilometres;
AUKMD = total distance all autos are driven by all household members as part of *discretionary* tours, in kilometres;

TOURC = number of *compulsory* tours undertaken by all household members using any mode;
TOURD = number of discretionary tours undertaken by all household members using any mode;
CATTC = average number of trips per *compulsory* tour for all household members together by all modes;
CATTD = average number of trips per *discretionary* tour for all household members together by all modes;
CADTC = average distance travelled per trip for all household members on *compulsory* tours by all modes;
CADTD = average distance travelled per trip for all household members on *discretionary* tours by all modes;
CPDAC = proportion of total distance travelled by all household members as auto driver on *compulsory* tours; and
CPDAD = proportion of total distance travelled by all household members as auto driver on *discretionary* tours.

VKT and all the 10 variables included in the function-determining values for VKT are indicator variables. A separate regression equation is considered for each of these indicator variables using the same, or very similar, sets of explanatory variables, allowing the various influences to be assessed separately.

The number of private vehicles owned by the household, represented by the variable HAUTO, is also included as both an indicator variable and an explanatory variable in the system of equations.

Explanatory Variables

The explanatory variables included in the observations of household travel behaviour fall into three basic categories:

- indications of urban form;
- indications of household size and socioeconomic status; and
- indications of household travel behaviour and related conditions, including some of the indicator variables listed above (in that, for example, the number of compulsory tours undertaken by a household will have some influence on the number of discretionary tours made).

The variables regarding urban form can be grouped as follows:

- measures of built form density;
- measures of activity density;
- behavioural choice model accessibilities;
- opportunity-shed accessibilities; and
- neighbourhood road patterns.

Measures of built form density

Variables in this group concern the spatial density of dwelling units in the ETA around the dwelling. The specific variables included are defined as follows:

DWPHA = dwelling units per gross developable hectare in ETA zone containing home location; and
PDUHA = total potential dwelling units per gross developable hectare in ETA zone containing home location.

Activity density variables

Variables in this group concern the spatial density of residential or employment activity in the ETA of the dwelling. The specific variables included are defined as follows:

POPHA = people per gross developable hectare in ETA zone containing home location;
HHPHA = households per gross developable hectare in ETA zone containing home location;
EMPHA = jobs per gross developable hectare in ETA zone containing home location; and
PHHHA = total potential people per gross developable hectare in ETA zone containing home location.[1]

It was judged that population density rather than dwelling unit density gives a more accurate representation of the "comparative closeness" of people and the related opportunities and

constraints regarding travel. Consequently, both dwelling unit and population density values are included in this study, but population density enjoyed much more use in the estimations.

It is also worthwhile to note at this point that many newer suburban neighbourhoods in Edmonton have a relatively high population density of 3,500 to 4,500 persons per square kilometre, corresponding to about 10 to 15 residential units per hectare. These suburban densities are as high as many older inner city neighbourhoods, and are significantly higher than densities typical of the suburbs of American and Canadian cities (Raad and Kenworthy, 1998). This means that the correlations between population density and other aspects of urban form that tend to vary systematically with increasing distance from the city centre are not as strong as they might be in this study, thereby allowing the estimation process to separate more completely the different influences involved.

Behavioural choice model accessibilities

Variables in this group concern the spatial distribution and magnitude of activities and the ease of travel between these activities as provided by the transport systems connecting them. A location's accessibility increases as the number of activities near it increases and as the utility of travel (ease, time, costs, attractiveness) to these activities increases. Consider Figure 1 in which location X has a greater accessibility to jobs than does location Y.

The utility of travel for autos includes the impacts of in-vehicle (or riding) time, parking costs, operating costs and extent of opportunities for car pooling. The utility of travel for transit includes the impacts of in-vehicle time, walking time, service frequency, number of transfers and transit fares. Utility functions for walking and cycling include impacts of distance and the facilities available. Accessibility values are considered for both home locations and workplace locations.

The definitions for this set of explanatory variables are as follows:

AACHZ = *auto* accessibility for the ETA zone containing home location;
TACHZ = *transit* accessibility for the ETA zone containing home location;
WACHZ = *walk* accessibility for the ETA zone containing home location; and
BACHZ = *bike* accessibility for the ETA zone containing home location.[2]

Variables for these modes are also included for "work location of designated head of household" and "work locations for all employed household members." Variables for "transit service availability for ETA zone containing home location" and "transit service availability for ETA zone containing work locations of household members" are also included.

Opportunity-shed accessibilities

Variables in this group concern the spatial distribution, magnitude of activities and the ease of travel among these activities in much the same way as those in the previous group. However, in this group, the number of activities is calculated within specified time bands for a given mode. For example, shopping accessibility by walking for a given location is provided using three values: the total shopping employment that can be reached within a 15-minute walk, within a 30-minute walk, and within a 45-minute walk. In Figure 2, location X has a higher accessibility by walking than location Y.

These accessibility variables are mode-specific, similar to those of the previous group, in that they provide separate representation of the impacts of different public transport service densities and different levels of physical provision for pedestrian and bicycle travel. However, they are not based on any calibrated model, which distinguishes them from those of the previous group. This lack of any basis in a calibrated model can be seen as both positive and negative: the behavioural basis of the variables is not as strong, but there is also no reliance on any previously determined parameter estimates thereby allowing the indications in the observations to emerge more directly.

Figure 1
Accessibility to Employment

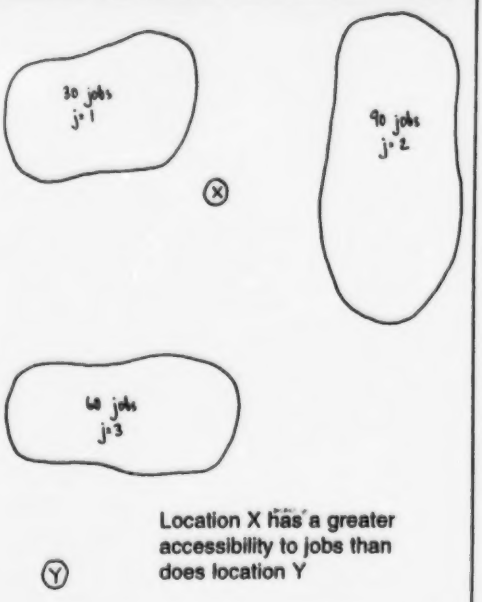
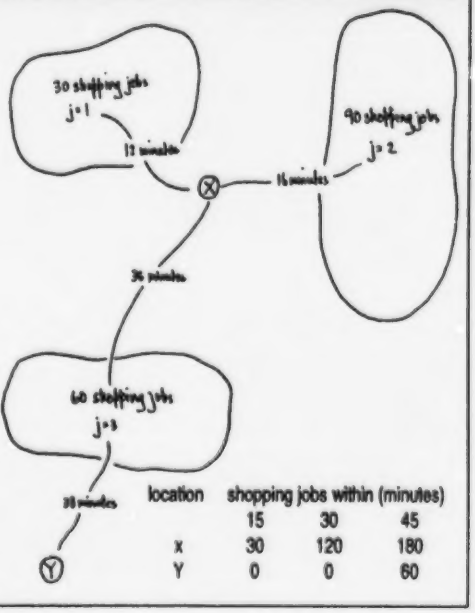


Figure 2
Opportunity-shed Accessibilities to Shopping Activities



location	shopping jobs within (minutes)		
	15	30	45
X	30	120	180
Y	0	0	60

Neighbourhood road patterns
The variables in this group concern the layout of the road pattern and associated roadway hierarchy in the ETA around the dwelling. The specific variables are for the ETA zone containing the home location and whether they are: "strictly rectangular grid," "primarily rectangular grid with some diagonal breaks," "mix of rectangular grid and curvilinear," "regular curvilinear" or "random curvilinear."

Household size and socioeconomic status
The specific variables in this category are:

HSIZE = number of people in household;
HEMPF = number of full-time employees in household;
HEMPP = number of part-time employees in household;
HUEMP = number of unemployed in household;
HRETD = number of retirees in household;
HHMKR = number of homemakers in household;
HPRES = number of preschoolers in household;
HELMS = number of elementary students in household;
HJHSS = number of junior high school students in household;
HSHSS = number of senior high school students in household;
HNGSC = number of grade school students in household;
HHPSE = number of post-secondary students in household;
HWATH = number of employees working at home in household;
HAUTO = number of private vehicles in household;
HINCM = household total annual income;
HDRVR = number of licensed drivers in household; and
AUAV = household auto availability, which is the ratio of the number of private vehicles in household over the number of licensed drivers in household.

Table 1:
Explanatory variables included in estimation runs

Variable Type	Variable Detail	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16	Run 17	Run 18
HOUSEHOLD DEMOGRAPHICS	Size	•	•	•	•	•							•	•	•	•	•	•	•
	Person type	•	•	•	•	•							•	•	•	•	•	•	•
	Income	•	•	•	•	•							•	•	•	•	•	•	•
	Auto ownership	•	•	•	•								•	•	•	•	•	•	•
DENSITY FOR HOME ZONE	Existing population density	•	•	•	•				•	•		•	•	•	•	•	•		
	Employment density	•	•	•	•				•		•	•	•	•	•	•	•		
	Ultimate population density	•	•	•	•				•				•	•	•	•	•		
NEIGHBOURHOOD ROAD PATTERN		•	•	•	•		•						•	•	•	•	•	•	•
ACCESSIBILITY (behavioural model) FOR FOR HOME ZONE	Auto	•	•	•	•			•										•	
	Transit		•	•	•			•										•	
	Walk	•	•	•	•			•										•	
	Bicycle	•	•	•	•			•											
ACCESSIBILITY (opportunity shed) FOR HOME ZONE	Auto				•										•	•			•
	Transit			•										•		•			
	Walk		•										•			•			
	Bicycle															•			
ACCESSIBILITY (behavioural model) FOR FOR WORK ZONE	Auto	•	•	•	•				•									•	
	Walk	•	•	•	•				•									•	

Household travel behaviour and related conditions

Some of the indicator variables listed above can also be treated as explanatory variables. For example, as the number of compulsory tours undertaken by a household (represented by the indicator variable TOURC) increases, it can be expected that this would lead to a reduction in the number of discretionary tours (represented by the indicator variable TOURD), all other things being equal. This would be considered here by including TOURC as an explanatory variable in the regression equation for TOURD. Overall, just TOURC and TOURD are included as explanatory variables in certain regression equations.

Estimation Approach

A series of 18 separate estimation "runs" were performed using the SHAZAM computer package (White, 1997), each considering the full system of equations. In each run, the individual regression equations were estimated separately. A different combination of explanatory variables was considered in each run, with Table 1 providing a summary of the explanatory variables included in each case. The intention with the entire series of estimation runs was to isolate and understand the effects of specific elements of urban form. To this end, various explanatory variables concerning density, accessibility and neighbourhood road layout were considered alone and in combination with other variables over the series of runs.

Developing Indications from Estimation Results

The results of the various estimation runs provide the indications of the influences of specific factors on the quantity of private vehicle use. In particular, the estimation results for specific parameters and the impacts of sets of explanatory variables on the overall goodness-of-fit of the regression equation form the basis for the indications regarding the influences of the associated factors.

In developing the discussions in Chapter 5, the estimates for specific parameters were reviewed with regard to sign and relative magnitude, and instances where these were inconsistent with expectations were given further consideration. Relevant mean-value point elasticities of the indicator variables with respect to specific explanatory variables were also considered. The statistical significance of the estimates for parameters was considered using standard errors and t-ratios, where the t-ratio for an estimate is the value of the estimate over the value of the standard error of the estimate. A t-ratio greater than 1.5 in absolute magnitude was deemed to indicate that the parameter was unlikely to have a true value of 0. In such cases, the estimate is referred to as "significant."

The impacts of sets of explanatory variables on the overall goodness-of-fit of regression equations were considered using the standard R^2 statistic, along with an adjusted form, R^2_{adj}, that decreases in value as the number of explanatory variables in the regression equation increases, thereby favouring simpler models.

Indications from Sensitivity Analysis

The behavioural choice model accessibility variables discussed previously are composite measures that reflect the combined effect of a number of different component factors, such as parking costs, travel times and the spatial distributions of activities. In order to obtain a more complete picture of the influences of each of these various component factors on private vehicle use, some further sensitivity analysis was conducted. The component accessibility variables were individually reduced by 10 per cent and the change in total auto use was observed.

The estimation results were used to develop a sample enumeration process that provides an estimate of the aggregate total auto use for the "population" of Edmonton households. The value for VKT for each household in the sample is calculated using the results for regression equation 17 (selected as the "best" of those considered) and then factored by an appropriate "weighting factor" to establish a value for the corresponding population of households

represented by that observation. The values for all observations are then summed to get the estimate of total VKT for the entire population of households represented by the entire sample. Further, an estimate of the aggregate total auto use for a specific subgroup of the population of Edmonton households can be obtained by including only those observations of households in the subgroup in the summation.

In the sensitivity analysis, the sample enumeration process was first used with all the component variables affecting accessibility and all the other explanatory variables set to their observed values. This provided a "base case" estimate of the aggregate total auto use. Then the value for a given component variable was changed, by reducing it by 10 per cent, while the values for all the other explanatory variables were held constant and the sample enumeration process was used again to determine a new estimate. This was then compared with the "base case" estimate in order to determine the change in aggregate total auto use occurring with the change in the component variable.

The component factors of accessibility considered in this way included:

- walking times (simulating the effect of moving home and activity locations closer);
- in-vehicle travel times for auto;
- in-vehicle travel times for transit;
- in-vehicle travel times for all modes (auto, walk and transit);
- parking costs;
- road capacity;
- speeds on collector roadways;
- transit fares;
- walking times for transit; and
- waiting times for transit.

5. FINDINGS

This chapter discusses the results of the various estimations and of the sensitivity analysis, summarizing them and drawing out the indications provided concerning influences on household private vehicle use, in particular, and travel behaviour, generally.

Goodness-of-Fit Results

The overall goodness-of-fit of the estimated regression equations for the different indicator variables establishes the overall explanation provided by the different sets of explanatory variables. In no case is R^2_{adj} for any of the 18 runs close to 1, and in some cases it is quite close to 0. The values tend to get higher as the number of explanatory variables increases, which is to be expected in that more explanatory variables provide more information to use in a given explanation all other things being equal. The highest values are for the equations for TOURC, the number of compulsory tours. These values approach 0.65 when there are a comparatively large number of explanatory variables. The lowest values are for the equations for CATTC, CATTD and CADTD, the average number of trips per *compulsory* tour and per *discretionary* tour and the average distance per trip for *compulsory* tours by all modes, respectively. These values are all less than 0.1, even with comparatively large numbers of explanatory variables.

Overall, these low R^2_{adj} values indicate that much of the variation in household travel behaviour is not explained by the regression equations. This is perhaps not too surprising. Household travel behaviour is in itself highly variable.

Variations in HAUTO, the number of private vehicles owned by members of the household, are better explained by the variables considered here relative to the variations in most of the other facets of household travel behaviour, in particular when a relatively large number of explanatory variables are included. Auto ownership does not vary on a daily basis, which means that some unexplained variation present in other facets of household travel behaviour is avoided and a better explanation should be expected.

Overall, the factors considered here are able to explain relatively more of the variation in compulsory travel than in discretionary travel, which seems reasonable given the number of employment-related and education-related variables included as explanatory variables. This is also consistent with the idea that households have relatively invariant underlying needs. Either the number of stops per tour is inherently highly variable or it is largely dictated by factors other than those being considered here. The same is true for the average distance per trip on discretionary tours in particular.

Amount of Private Vehicle Use (VKT) Estimation Results

This section focusses on the results for VKT specifically, considering the indications provided in the estimation results regarding the significance of the influences of the explanatory variables on the amount of private vehicle travel. Table 2 lists the values found for the statistically significant parameter estimates and the corresponding R^2_{adj} indices for the 18 estimation runs.

A comparison of the R^2_{adj} values indicates that the best explanations of variation in VKT are obtained when the following sets of explanatory variables are included:

- demographic variables;
- all mode-specific accessibilities for the zone containing the home location, either behavioural choice model accessibilities or opportunity-shed accessibilities;

Table 2:
Elasticity at means for significant parameter estimates and R^2_{adj} indices for estimation runs

Type	Variable	Run 1 Variable	Run 1 Elasticity at means	Run 2 Elasticity at means	Run 3 Elasticity at means	Run 4 Elasticity at means	Run 5 Elasticity at means	Run 6 Elasticity at means	Run 7 Elasticity at means	Run 8 Elasticity at means	Run 9 Elasticity at means	Run 10 Elasticity at means	Run 11 Elasticity at means	Run 12 Elasticity at means	Run 13 Elasticity at means	Run 14 Elasticity at means	Run 15 Elasticity at means	Run 16 Elasticity at means	Run 17 Elasticity at means	Run 18 Elasticity at means
R^2_{adj}			0.329	0.330	0.330	0.334	0.216	0.088	0.201	0.042	0.035	0.019	0.040	0.320	0.321	0.325	0.328	0.306	0.329	0.320
HOUSEHOLD DEMOGRAPHICS	HAUTO	HAUTO	0.436	0.438	0.440	0.436								0.473	0.475	0.468	0.468	0.501	0.434	0.464
	HSIZE	HSIZE	0.219	0.216	0.215	0.216	0.466							0.206	0.206	0.204	0.196	0.207	0.210	0.195
	HINCM	HINCM	0.150	0.143	0.145	0.138	0.325							0.135	0.138	0.135	0.120	0.143	0.152	0.144
	HEMPF	HEMPF	0.141	0.144	0.143	0.144	0.239							0.156	0.155	0.153	0.161	0.154	0.149	0.176
	HNGSC	-HNGSC	-0.021	-0.021	-0.020	0.020	-0.039												-0.017	
	HSHSS	HSHSS	0.019	0.019	0.019	0.019	0.023							0.019	0.018	0.018	0.018	0.018	0.019	0.018
	HEMPP	HEMPP	0.017	0.018	0.018	0.018	0.036							0.020	0.019	0.019	0.020	0.019	0.019	0.023
	HWATH	HWATH	0.006	0.006	0.006	0.006	0.010							0.007	0.007	0.007	0.007	0.007	0.006	0.007
	HRETD	-HRETD												-0.014	-0.012	-0.012	-0.011	-0.011		
HOUSEHOLD ZONE DENSITY	POPHA	-POPHA								-0.574	-0.307		-0.257			-0.150		-0.135		
	PHHHA	PHHHA								0.351					-0.125					
	EMPHA	-EMPHA								-0.029		-0.051	-0.028					-0.007		
NEIGHBOURHOOD ROAD LAYOUT	NRGDL	-NRGDL	-0.013	-0.015	-0.016	-0.012		-0.072						-0.030	-0.023	-0.016	-0.026	-0.034	-0.016	-0.022
	NRGCL	NRGCL	0.012	0.011	0.012	0.006		0.025						0.014	0.015	0.005		0.023	0.012	0.010
	NRGDM	-NRGDM	-0.012	-0.016	-0.023			-0.121						-0.023	-0.032	-0.017	-0.030	-0.040	-0.015	-0.021
	NRCCL	-NRCCL						-0.011							0.124					
HOUSEHOLD ZONE ACCESSIBILITY (Behavioural)	AACHZ	AACHZ	0.460	0.415	0.344	0.478			0.771										0.398	
	TACHZ	-TACHZ							-0.018										-0.016	
	NTAOH	NTAOH	0.035	0.024	0.020				0.048										0.050	
	WACHZ	-WACHZ							-0.062										-0.091	
	BACHZ	-BACHZ	-0.188	-0.187	-0.208				-0.383											
HOUSEHOLD ZONE ACCESSIBILITY (Opportunity Based)	AAT45																			0.647
	AAS45	AAS45				7.761										8.504	5.756			
	AAR45	-AAR45				-6.466										-7.150				
	AAT30																			-0.584
	AAJ30	AAJ30				2.445										1.840	2.813			
	AAN30	-AAN30				-2.281										-2.007	-2.364			
	AAS30	-AAS30				-0.609														
	AAT15																			-0.072
	AAN15	AAN15				0.463										-0.864				
	AAJ15															0.661				
	TAT30	TAT30			0.103															
	TAR30	-TAR30			-0.063															
	TAS30	-TAS30		0	-0.041										-0.049		-0.054			
	TAP30	-TAP30			-0.021										-0.023		-0.030			
	TAP15														-0.006					
	TAN15																-0.075			
	WKN45	-WKN45												-0.270			-0.201			
	WKR15	WKR15												0.019						
	WKP30	-WKP30												-0.006						
	WKP15	-WKP15												-0.003						
	BKT45																-0.363			
	BKR45																0.537			
	BKS15	-WKP15												-0.003			0.105			
WORK ZONE ACCESSIBILITY (Behavioural)	AAAWZ	AAAWZ							0.401										0.055	
	WAAWZ	-WAAWZ	-0.017	-0.017	-0.017	-0.017			-0.024										-0.017	

- auto and walk behavioural choice model accessibilities for the zone containing the work location; and
- neighbourhood road patterns.

Table 3 summarizes some of the R^2_{adj} values obtained when certain groups of explanatory variables are included on their own. Household demographic and both home and work accessibility variables, by themselves, explain more variation in VKT than do either neighbourhood road pattern or density variables. These household demographic and accessibility variables retain significant parameter estimates in all the runs where they are included. Neighbourhood road pattern variables also consistently demonstrate a small but significant influence on VKT.

Table 3:
Goodness-of-fit results for selected groups of explanatory variables

Groups of Explanatory Variables	R^2_{adj}
Household demographics	0.22
Home and work zone accessibilities	0.2
Neighbourhood road patterns	0.08
Home zone densities	0.02-0.04

However, regarding the density variables, there is a strong general pattern where the parameter estimates for residential and employment density variables are significant only when certain other variables are excluded. Specifically, they are insignificant when household demographic and accessibility variables are included. For example, results for runs 1, 8 and 9 display the following.

- When POPHA (population per hectare), EMPHA (jobs per hectare) and PHHHA (potential population per hectare) are the only explanatory variables, then their estimated coefficients are all significant.

- When POPHA is alone, then its estimated coefficient is significant and the associated elasticity at means value is negative, consistent with expectations and relatively large in absolute magnitude, suggesting a strong influence.

- But, when other explanatory variables are included, then the estimated coefficients for POPHA, EMPHA and PHHHA are all insignificant and the associated elasticity at means values are relatively small.

Furthermore, the R^2_{adj} values are much higher when other explanatory variables are included. All this suggests that the estimated parameters are biased when POPHA, EMPHA and PHHHA are the only explanatory variables, because the included variables are correlated with the excluded variables, and thus the parameter estimates are "picking up" a combined effect. This is expected to have led to conclusions in other work where density variables were considered in isolation, such as the studies by Newman and Kenworthy (1989a, 1989b).

The regression equation for VKT from Run 17 is selected for further consideration regarding certain specific indications for the following reasons.

- It includes a reasonably complete set of the strongest explanatory variables.

- It has a comparatively high value for R^2_{adj}.

- All its estimated parameter values are significant.

- Compared with the other equations considered for VKT, its estimated parameters are the most consistent with expectation in terms of signs and relative magnitudes.

These reasons altogether indicate that the regression equation for VKT from Run 17 does the best job of explaining auto use behaviour out of those considered. Note that some of the density variables considered in the analysis did not display significant influences and thus were not included in Run 17.

The t-ratios and the elasticity at means values for the variables with significant parameter estimates in the equation for VKT are listed in Table 4. The corresponding values for the remaining variables with insignificant parameter estimates are listed in Table 5.

Table 4:
Results for significant explanatory variables for VKT

Variable	Description	t-ratio	Elasticity at mean
HAUTO	Number of private vehicles in household	18.0	0.434
HINCM	Annual household income category	5.2	0.152
HSIZE	Number of people in household	5.5	0.210
HEMPF	Number of full-time employees in household	7.0	0.149
HEMPP	Number of part-time employees in household	3.2	0.019
HSHSS	Number of senior high school students in household	4.9	0.019
HNGSC	Number of grade school students in household	-1.5	-0.017
HWATH	Number of employees working at home in household	3.1	0.006
NRGDM	Strict rectangular grid road pattern in home zone	-1.9	-0.015
NRGDL	Primarily rectangular grid road pattern in home zone	-2.8	-0.016
NRGCL	Mix of rectangular grid with curvilinear pattern in home zone	4.0	0.012
AACHZ	Automobile accessibility for home zone	4.5	0.398
TACHZ	Transit accessibility for home zone	-2.1	-0.016
NTAOH	Transit "not available" in home zone	10.0	0.050
WACHZ	Walk accessibility for home zone	-4.1	-0.091
AAAWZ	Automobile accessibility for work zone	2.0	0.055
WAAWZ	Walk accessibility for work zone	-6.2	-0.017

Table 5:
Results for insignificant explanatory variables for VKT

Variable	Description	t-ratio	Elasticity at mean
NRCCL	Regular curvilinear road pattern in home zone	0.1	0.001
POPHA	Persons per gross developable km^2 in home zone	1.4	0.034
EMPHA	Jobs per gross developable km^2 in home zone	0.6	0.003

Indications from Significant Parameter Estimates for VKT

Some of the specific indications provided by the relative magnitudes of the t-ratios and elasticity at means values in Table 4 are as follows.

- The number of private vehicles owned by household members (HAUTO) is the single most important household explanatory variable, with an elasticity at means value of 0.434, which is positive as expected. Note that HAUTO is, in turn, strongly related to a range of household demographic variables, including income, size and number of workers.
- Household demographic variables, have a strong impact on VKT. Household income, size and number of full-time workers have the strongest influences. Variables related to ages and employment status[2] have smaller but still significant influences. This is consistent with other studies (Ewing, 1995; Kitamura et al., 1994; Schimek, 1996).
- The mode-specific accessibilities for the home zone have strong influences on the quantity of auto use. In particular, the auto accessibility for the home zone, AACHZ, has a strong positive influence on VKT consistent with expectations. The elasticity at means value of 0.398 is the second highest out of the

explanatory variables included. The walk accessibility for the home zone, WACHZ, has a moderate negative influence and the transit accessibility for the home zone, TACHZ, has a relatively small but still significant negative influence on VKT, again consistent with expectations. A complete absence of transit service in the home zone, as indicated by NTAOH, has a moderate additional positive influence on VKT consistent with the results for TACHZ. The results for NTAOH and TACHZ together imply that the level of transit service supplied is less important than the fact that some form of transit service is available at all. This may be related to the design of the Edmonton transit system where there are minimum standards of service for most neighbourhoods, and the fact that there is a flat fare system irrespective of distance travelled or routes used.

- The auto and walk accessibilities for the work zone are shown to influence the quantity of auto use in much the same way as the corresponding values for the home zone, but at somewhat reduced strengths. In particular, the auto accessibility for the work zone, as indicated by AAAWZ, has a moderate positive influence on VKT, whereas the walk accessibility for the work zone, as indicated by WAAWZ, has a relatively small negative influence on VKT. These results are consistent with the idea that a greater ability to walk and a lesser ability to drive to destinations for workers, perhaps during lunchtime, will act to reduce the dependency on, and thus the use of, automobiles.

- The number of people working at home, HWATH, has a small but significant positive influence on VKT. This contradicts some current thinking about the potential benefits of having more people work at home, perhaps telecommuting. The results obtained here, for all the indicator variables, not just VKT, and for runs other than just Run 17, indicate that households with people working at home do tend to travel less on compulsory tours, but also tend to make more discretionary tours with more stops, longer trips and a greater proportion of private vehicle use, with the net result that they tend to use the car more rather than less overall.

- The neighbourhood road pattern in the area around the home has a relatively small but significant influence on the quantity of auto use, as indicated by the results for NRGDM, NRGDL and NRGCL variables. The small and negative elasticity at means values for the strict rectangular and primarily rectangular grid patterns suggest that these patterns tend to bring about a slight reduction in private vehicle use relative to the random curvilinear pattern. This is broadly consistent with the thinking regarding the impacts of neo-traditional development on auto dependency, although the magnitude of the effect indicated here may be somewhat less than is sometimes implied in the claims made concerning the benefits of neo-traditional development (Active Living, 1996; Adler, 1995; Bookout, 1992a, 1992b; Crane, 1996a, 1996b; Duany and Plater-Zyberk, 1991, 1992). The small and positive elasticity at means value for the mix of rectangular and curvilinear patterns suggests that this pattern tends to bring about a slight increase in private vehicle use relative to the random curvilinear pattern.

Indications from Insignificant Parameter Estimates for VKT

Some of the specific indications provided by the results in Table 5 are as follows.

- Population density, as represented by POPHA, does not have a significant influence on private vehicle use when regressed simultaneously with the other explanatory variables. Its (insignificant) parameter estimate is 0.00059, and the associated elasticity at means value is 0.0339. This positive elasticity at means value indicates that increasing residential density acts to increase private vehicle use, although in this case there can be little confidence in this indication given the lack of significance of the corresponding parameter estimate. Overall,

these results appear to contradict those obtained in other studies, where population density was found to have a strong negative influence on private vehicle use. However, some studies used population density measures for entire cities and considered behaviour across different cities, which is different than the use of population density measures for neighbourhoods and observations of behaviour from just one city as is done in this study. Further, in some of these other studies the effect of density was considered without also including accessibility measures and without using multiple regression, as was done in this study. Excluding other variables such as accessibility measures has a biassing effect on the apparent influences of densities, as discussed above.

- Employment density, as represented by EMPHA, does not have a significant influence on VKT. Its (insignificant) parameter estimate and the associated elasticity at means value are positive and even smaller than those for POPHA. The comments made immediately above concerning POPHA also apply concerning EMPHA.

- Regular curvilinear neighbourhood road patterns in the home zone, as represented by NCR, do not have any discernible effect on VKT relative to random curvilinear neighbourhood road patterns. This, together with the results for the rectangular patterns described above, suggest that the important distinction in neighbourhood road patterns vis-à-vis the quantity of private vehicle use concerns the shape (rectangular grid versus curvilinear) rather than the regularity (random versus regular) of the pattern.

Further Issues Concerning Estimations for VKT

Some specific indications provided by the results of the full set of runs are as follows.

- In most runs the estimated parameter for NRETD, the number of retired people in the household, is insignificant.

- The bike behavioural mode choice accessibility variable, BACHZ, represents much the same effects as the walk and transit accessibility variables, WACHZ and TACHZ respectively, and is highly correlated with these variables as a result, with correlation coefficients of 0.732 and 0.768 respectively. In most cases where BACHZ is included as an explanatory variable with WACHZ and TACHZ, the estimated parameter for WACHZ is negative, consistent with expectations, but not significant. But where BACHZ is not included, the parameter estimate for WACHZ is negative and significant. The walk mode is judged to be of more relevance than the bike mode generally, which leads to a preference for a specification where WACHZ is included and BACHZ is not, as is done in Run 17, rather than one where the parameter estimate for WACHZ is insignificant. It is important to recognize that when BACHZ is excluded the parameter estimate for WACHZ includes some of the effects of bike accessibility and thus, in the strictest sense, is biased. But it is judged that such a representation is reasonably consistent with reality, where the conditions that influence walk accessibilities also influence bike accessibilities in much the same way. Thus, changes in one will be highly linked with changes in the other such that including representation of just one provides an appropriate representation of the effects of both.

- In general, the parameter estimates for the various opportunity-shed accessibility variables are not significant, and it is difficult to see any strong consistent patterns in the signs or the relative magnitudes of the estimates. This lack of significance and of consistent patterns may be, in part, due to the relatively large number of parameters involved, where too much is being required of the information available in the data. The results for the behavioural mode choice accessibility variables are much stronger and involve fewer parameter estimates. The behavioural mode choice accessibility variables also use a more complete and continuous representation of the factors influencing travel in that they are based on a travel utility that combines various weighted components of

travel time and cost. All this leads to a very strong preference for the behavioural mode choice measures rather than the opportunity-shed measures for the accessibility variables.

Private Vehicle Ownership (HAUTO) Estimation Results

The estimation results for VKT indicate that the number of private vehicles in the household, HAUTO, has a very strong positive influence on the quantity of private vehicle use. Table 6 lists the t-ratios and the elasticity at means values for the variables in the equation for HAUTO with significant parameter estimates, and Table 7 lists the corresponding values for the variables with insignificant parameter estimates. The results for HAUTO are broadly similar to the results for VKT. This is perhaps not too surprising given the strong influence that HAUTO has on VKT.

As is the case with VKT, the best explanations of variation in HAUTO are obtained when the following types of explanatory variables are included:

- demographic variables;
- all mode-specific accessibilities for the zone containing the home location, either behavioural choice model accessibilities or opportunity-shed accessibilities;
- auto and walk behavioural choice model accessibilities for the zone containing the work location; and
- neighbourhood road patterns.

The number of people in the household, the automobile accessibility for the home zone and annual household income have the strongest influences on auto ownership.

Estimation Results for Other Indicator Variables

Table 8 presents the relative magnitude, direction and statistical influence of the explanatory variables on each component of household travel behaviour for Run 17 in particular.

Overall, the effects of specific explanatory variables on a range of travel components in some

Table 6:
Results for significant explanatory variables for HAUTO

Variable	Description	t-ratio	Elasticity at mean
HINCM	Annual household income category	18.4	0.287
HSIZE	Number of people in household	20.2	0.408
HEMPF	Number of full-time employees in household	10.1	0.118
HEMPP	Number of part-time employees in household	8.0	0.025
HSHSS	Number of senior high school students in household	4.5	0.010
HNGSC	Number of grade school students in household	-15.3	-0.091
HWATH	Number of employees working at home in household	4.0	0.004
NRGDM	Strict rectangular grid road pattern in home zone	1.8	0.007
NRGDL	Primarily rectangular grid road pattern in home zone	3.0	0.010
NRCCL	Regular curvilinear road pattern in home zone	3.5	0.008
NRGCL	Mix of rectangular grid with curvilinear pattern in home zone	2.9	0.005
AACHZ	Automobile accessibility for home zone	8.1	0.390
TACHZ	Transit accessibility for home zone	-1.9	-0.008
NTAOH	Transit "not available" in home zone	8.1	0.022
WACHZ	Walk accessibility for home zone	-6.1	-0.074
AAAWZ	Automobile accessibility for work zone	-2.3	-0.035
WAAWZ	Walk accessibility for work zone	-7.2	-0.011

Table 7:
Results for insignificant explanatory variables for HAUTO

Variable	Description	t-ratio	Elasticity at mean
POPHA	Persons per gross developable km² in home zone	0.0	0.000
EMPHA	Jobs per gross developable km² in home zone	-1.3	-0.003

cases differ widely from their impact on VKT. This may explain why other studies have obtained different indications of the influences of specific explanatory variables, depending on which indicator variables were considered. The findings regarding the density and accessibility variables, in particular, are outlined below.

Population and employment densities, POPHA and EMPHA respectively, both have moderate negative and significant influences on the proportion of travel by auto for compulsory tours. Employment density also has a small negative but significant influence on the number of trips per compulsory tour. All the other influences are not significant, and the influences on auto use overall are similarly not significant. The indications of significant negative influences on the proportion of travel by auto suggest that increased densities help make the mode alternatives to the car relatively more attractive and thus relatively more successful in attracting travellers away from their cars, at least for compulsory tours. This is consistent with the idea that transit is much more effective competition to the auto and can act to reduce the proportion of travel by auto when:

- neighbourhood densities are greater and thus the walking distances are sufficiently shorter; and
- the trips are being made many times, as is the case with compulsory trips to work and school, because the benefits arising from the effort required to learn about the transit system are then spread over a large number of individual journeys.

The results suggest that this specific influence of density acts in combination with the accessibility values for transit, walk and bicycle.

Auto accessibility in the home zone, AACHZ, overall has a strong positive influence on auto use overall. These results suggest that as auto accessibility increases, households tend to own more autos, make larger numbers of more extensive and automobile-intensive discretionary tours and make fewer but more extensive automobile-intensive compulsory tours, with the end result that they tend to make much greater use of autos overall.

Transit accessibility in the home zone, TACHZ, has a moderate negative and significant influence on auto use overall. These results suggest that, as transit accessibility increases, households tend to own slightly fewer autos and make larger numbers of less extensive compulsory tours, with the end result that they tend to make somewhat less use of autos overall.

The absence of transit in the home zone has influences consistent with those of transit accessibility. The net result is a moderate positive and significant influence on auto use overall. All this suggests that households located in zones without transit service tend to own more cars, make fewer, more complex and auto-intensive tours, with the net result that they make more use of autos overall. Again, it is important to stress that these results do not indicate a "direction" in this tendency. It could be (a) that the lack of transit causes households to become more auto dependent, or (b) that households that are more "auto-oriented" have less concern about transit and therefore have a greater tendency to locate where transit is not available or (c) some combination of both (a) and (b) above.

Walk accessibility in the home zone, WACHZ, has influences that match fairly closely those of transit accessibility in the home zone, although

Table 8:
Summary of results for all components of household trip making

VARIABLE NAME	Auto Distance Total UKT	Number Tours Compulsory TOURC	Trips per Tour Compulsory CATTC	Distance per Trip Compulsory CADTRC	Split to Auto Compulsory OPDAC	Number Tours Discretionary TOURD	Trips per Tour Discretionary CATTD	Distance Per Trip Discretionary CADTD	Split to Auto Discretionary OPDAD	Auto Ownership HAUTO
R^2_{adj}	0.329	0637	0.048	0.196	0.270	0.262	0.038	0.053	0.124	0.366
TOURC			—			—	-			
TOURD							-			
HAUTO	++++	++	++	+++	++++	+++	++	+++	++++	
HAUAV					++++				++++	
HINCM	+++	++	+++	++	+++	+++	-	—	—	++++
HSIZE++++	++++	–	–	—	++++		++	—	—	++++
HEMPF	+++	++++	-	++	+++	—	–	++	++++	+++
HEMPP	++	++	-	-	++	–	+	+	-	++
HSHSS	++	+	-	++	–	-	-	++	++	+
HNGSC	–	++++	+	—	—	—	+	–	+++	–
HWATH	+	–	-	-	–	++	++	++	++	+
NRGDM	–	–	-	–	–	-	+	++	–	+
NRGDL	–	–	-	–	–	-	+	+	++	+
NRGCL	++	-	-	++	-	-	+	++	–	+
NRCCL	+	-	-	+	-	-	+	+	+	+
POPHA	++	++	-	-	—	—	++	–	—	-
EMPHA	+	-	-	-	–	-	+	-	-	-
AACHZ	++++	—	++	++++	++++	+++	+++	++++	++++	++++
TACHZ	–	++	+	–	–	+	-	-	-	-
NTAOH	++	–	+	++	++	-	+	++	+	++
WACHZ	–	++	–	—	–	++	–	—	—	–
AAAWZ	++	++	+++	++	++++	++	–	-	++++	–
WAAWZ	–	+	+	–	—	-	-	++	-	–

Key: means variable "insignificant" - t-ratio <1.5

+	positive elacticity, less than 0.01	-	negative elacticity, less than 0.01
++	positive elasticity, between 0.01 and 1.10	--	negative elasticity, between 0.01 and 1.10
+++	positive elasticity, between -.1- and 0.20	---	negative elasticity, between -.1- and 0.20
++++	positive elasticity, greater than 0.20	----	negative elasticity, greater than 0.20

the influences of walk accessibility are perhaps a bit stronger. The results suggest that, as walk accessibility increases, households tend to own fewer autos and make larger numbers of less extensive and auto-intensive tours, with the end result that they tend to make less use of autos overall.

Auto accessibility in the work zone, AAAWZ, has a moderate positive and significant influence on auto use overall. These results suggest that as auto accessibility in the work zone increases, households tend to make larger numbers of more complex and auto-intensive compulsory tours and tend to use the auto for a greater proportion of travel on discretionary tours. This is not surprising since travel to work falls into the compulsory category.

The results for walk accessibility in the work zone, WAAWZ, suggest that as walk accessibility in the work zone increases, households tend to make slightly shorter, more complex compulsory tours involving much less auto use, while the number of compulsory tours is largely unaffected. This is consistent with the idea that workplaces with greater walk accessibilities encourage more walk-based touring out from work during lunch and other breaks. Household auto ownership is also reduced, consistent with expectations. The net effect is a reduction in auto use by the household.

Table 8 indicates that much of the explanation of the various facets of household travel behaviour considered is provided by the household demographic variables and the accessibility variables. The neighbourhood road pattern variables do not provide much explanation of behaviour regarding discretionary tours in particular, and the density variables do not provide much explanation apart from the proportion of travel by auto for compulsory tours.

Sensitivity Analysis Results

This section considers the indications arising from the results of the sensitivity analysis concerning the influences of specific components of accessibility on total auto use based on the equation for VKT from Run 17. Table 9 summarizes the results of the sensitivity analysis. Indications arising from these results are discussed below, first by category of component variable and then by geographic region of the household zone.

Impacts of mode travel time changes

A change in walk times (with all other times held constant) is shown to have the largest impact on auto use out of the accessibility components considered, with an elasticity for the total city of -3.25 per cent.[3] The negative sign is consistent with expectations, that is, as activities become closer together and walk times decrease, so does car use. In fact, the signs on the elasticities associated with the results of the sensitivity analysis are consistent with expectations in all cases, which adds further credence to the results.

A change in all mode "in" times has the next largest impact, with an elasticity for the total city of -0.241. This concerns the time spent in-vehicle for cars and transit, and in-motion for walking. A decrease in all mode "in" times is consistent with an increase in the density and mix of these activities, although auto "in" times are affected by other factors, such as flow rates.

A change in auto in-vehicle times has the next largest impact, and its elasticities are negative, consistent with expectations.[4] Changes in three transit-related variables (transit in-vehicle, wait and walk times) have the smallest impacts out of the various mode times considered. The elasticity of auto use with respect to transit in-vehicle time for the total city is the highest of the three variables, and it is only +0.063, which indicates the comparatively minor role of transit service on its own when considering the factors influencing auto use.

These results suggest that, all other things being equal, there will tend to be less auto use by households in neighbourhoods with better pedestrian linkages (which increases walk accessibilities on their own) and/or with higher activity densities and a greater degree of land-use

Table 9:
Summary of sensitivity analysis results showing changes in total auto use in response to 10% changes in various accessibility component variables

Accessibility Component Change	Inner Area	Suburbs	Total City
	%	%	%
Walk time down 10%*	-3.79	-3.02	-3.25
All mode "in" times down 10%*	-2.80	-2.25	-2.41
Car in-vehicle time down 10%*	+1.66	+1.44	+1.47
Transit in-vehicle time down 10%*	-0.68	-0.67	-0.63
Roadway capacities down 10%	-0.57	-0.46	-0.49
Gasoline cost up 10%	-0.50	-0.46	-0.46
Transit wait time down 10%	-0.48	-0.35	-0.40
Parking costs up 10%	-0.45	-0.26	-0.34
Parking costs up $0.50 **	-4.20	-2.80	-3.37
Transit walk time down 10%	-0.42	-0.23	-0.32
Transit fare down 10%	-0.34	-0.21	-0.27
Collector road speeds down 10%	-0.32	-0.24	-0.27

Notes:
* Reductions in travel times simulate the effect of moving activities physically closer together, and thus relate to changes in the density and land use mix.
** See Endnote 3.

mix (which increases all mode accessibilities). They also suggest that there will tend to be less auto use by households in neighbourhoods with improved transit services (which increases transit accessibilities on their own) but that the effect will be much more modest.

Impacts of road changes

A decrease in road capacity, that is, traffic volume, has a much smaller impact on auto use than does a corresponding change in auto travel times. It seems likely that this result is obtained, at least in part, because in Edmonton at the time of the data collection there was little traffic congestion. Even during peak periods, less than three per cent of the total kilometres of roadways were carrying traffic flows in excess of 95 per cent of capacity. Because the existing road network had this large spare capacity, the 10 per cent reductions in capacity considered in the sensitivity analysis had relatively little impact on travel times and thus had little impact on accessibilities.

A change in speeds on collector roads has the smallest impact on auto use out of all the accessibility components tested. The elasticity of auto use with respect to collector speeds is only +0.027. It would appear that this is the case, at least in part, because collector roads constitute only a small proportion of the total road network, and thus reductions in collector speeds affect only a small proportion of the travel times for the vast majority of auto trips. Further, auto travel times on collector roads in residential and other areas depend not just on operating speeds, but also on the number of stops at signals and stop signs, and the delay time in queues. This would further reduce the impacts of changes in just collector speeds on auto trip times, and thus on accessibilities.

Various forms of "traffic calming" where local roads are designed to encourage slower and more careful driving, for example, by narrowing lanes and making the driving more circuitous, may be seen as a way to discourage auto use by making driving slower and more difficult and thus less attractive. The results obtained here suggest that policies designed to discourage auto use by restricting the capacity of roadways or the speeds on collector roads (as with traffic calming) will

have little impact in Edmonton. However, these results do not address the effects of traffic calming per se, merely the effects of some of the capacity and speed changes that could result from traffic calming.

Impacts of mode cost change
Changes in travel costs have relatively less impact on auto use than do changes in corresponding travel times. A change in gasoline costs has the largest impact of the travel money cost components, with an elasticity of -0.046.

That a change in parking costs has relatively little impact is somewhat surprising given the prominent role of parking costs in travel demand analysis generally. But it appears that this result arises in part because there were no parking charges at many locations in Edmonton at the time of the survey. Parking charges were levied primarily in and around the CBD and at the major post-secondary education institutions. Increasing a zero cost by 10 per cent results in a cost that is still zero, so many of the parking costs remain unaffected and thus the real impact on auto accessibilities is muted in this analysis.

To provide further insight, an additional sensitivity test was conducted where parking charges are increased by a uniform aggregate amount of 50 cents per trip rather than by a percentage of the existing charge. The results for this change are shown in Table 9. This alteration brings about the largest change in auto use, but this result cannot be directly compared with the other elasticity values in Table 9 because it is an absolute, rather than a relative value. Nevertheless, the relatively dramatic response in this case would seem to be consistent with the idea that the low elasticity value obtained for a 10 per cent increase in parking costs is due to the zero base cost effect discussed above.

A change in transit fares has very little impact on auto use, which is consistent with the results concerning the other aspects of transit service considered.

Geographic variation in impacts of changes
The impacts of the various changes in components of accessibility are considered here for the inner area and suburbs of the city. For all the changes in components of accessibility considered, the impact on auto use is greater for the inner area households. It is possible that inner area households are more responsive to these changes because they tend to have a greater number of reasonable alternatives available. For example, when activities are already comparatively close together and transit is relatively convenient, such as in downtown areas, shifts to walking and transit become more viable and attractive.

Summary of Indications Provided by Results

The principal indications concerning the influences on household auto use provided by the results of the estimations and of the sensitivity analysis are as follows.

- The explanations of variation in household travel behaviour provided by the regression equations are not all that strong for most aspects of travel behaviour considered. The explanations provided for compulsory travel are better than those provided for discretionary travel. It is expected that the inherent random variation in travel behaviour from day to day in a given household contributed to this lack of explanation.

- As a group, the household demographic variables have the largest influences on the quantity of auto use by of the four groups of explanatory variables examined. Of these, household car ownership has the biggest influence, followed by household size, income and the number of full-time workers. In all cases, these influences are positive, consistent with expectations. The types of other persons in the household have smaller but still significant influences on auto use.

- Household car ownership is influenced by the same set of household demographic variables considered above, particularly household size,

income and the number of full-time workers. Again, these influences are all positive and consistent with expectations.

- Increasing auto accessibility in residential locations results in strong increases in both car use and car ownership.

- Increasing walk accessibility in residential locations results in moderate reductions in auto use.

- Both the presence of transit service and increased transit accessibility in residential locations results in minor decreases in both auto ownership and auto use.

- Increasing walk accessibility at work locations results in minor decreases in auto use, primarily due to shorter distances between activities and less auto use on compulsory tours.

- Auto accessibility at work locations increases auto use. It results in increases in the proportion of travel by auto and moderate increases in the number and complexity of compulsory tours.

- Densities are not found to be significantly related to household auto use overall in the case where other explanatory variables, such as household demographics and mode-specific accessibilities, are included in the equations, due to the correlation of these factors with density. When considered as the sole explanatory factor, densities do appear to be strongly negatively related to private vehicle use. Notwithstanding, densities do have a significant negative influence on the proportion of travel by auto for compulsory tours, in particular, even when other explanatory variables are included.

- Mode-specific accessibilities are better explainers of auto use than density. An important component of the mode-specific accessibilities, as determined by the sensitivity analysis, is the spatial distribution of activities, that is, how physically close are activity destinations, such as employment, shopping and so on. While density is a factor, accessibilities account for the combined effect of density and land-use mix. For example, in a high-density neighbourhood that is exclusively residential and shopping, school, employment, etc. are not located nearby, walk and transit accessibility would be low.

- Reducing walk times has the largest impact on aggregate auto use out of all the accessibility components considered, resulting in a reduction in car use, as expected. The next largest impact results from reducing all mode "in" travel times, that is, reducing time spent in the car, on transit or walking, which also results in less auto use. A decrease in these times is consistent with an increase in the density and mix of population and employment activities. Other accessibility components have lesser impacts on aggregate auto use, including transit service levels, transit fares, roadway capacities and collector road speeds. In all cases, the sign of the influence, positive or negative, is consistent with expectations.

- Increasing parking costs by 50 cents resulted in a large decrease in auto use, although this result is not directly comparable to the other accessibility components listed above, since the change is measured in cents rather than percentage.

- Neighbourhood road patterns have a relatively minor influence on private vehicle use consistent with expectations.

6. COMPARISON WITH OTHER STUDIES

Whereas other studies have found that population and employment densities have significant influences on auto use, this study found that the parameter estimates for such densities are only significant when variables such as mode-specific accessibilities are not included as explanatory variables. This study found that when accessibilities are included they are significant and densities are not. They are much more comprehensive representations than density values. In fact, they include the effects of density and mix of activities, so it is not surprising that they usurp the role of density values in explaining travel behaviour. All this provides a strong indication that these mode-specific accessibility values are more appropriate explanatory variables than density measures alone when considering household auto use.

There is general agreement from previous studies that land use has a direct influence on household travel behaviour, but there is not general agreement on the specific nature and magnitude of these influences. As indicated in the literature review, it is felt that much of this lack of agreement arises because of differences in study method and the associated indicator and explanatory variables used.

A previous study by Schimek (1996) used an approach comparable to the one used in this study. Schimek analyzed data concerning annual vehicle miles travelled by a sample of U.S. households using a system of two multiple-linear regressions, one concerning auto ownership and the other considering auto use. Residential density was included as an explanatory variable, and accessibilities were not. Table 10 compares the results of the Schimek study with the results of this study. The influences of demographic and transit variables are reasonably similar and, in some cases, very close. The one exception is the number of workers in the household, which has a much greater influence in the Schimek study. This difference could be, in part, due to the addition of further household composition variables in this study. The important contributions of the mode-specific accessibilities in this study can also be seen. In general, such a level of agreement among two studies in this field is remarkable.

Table 10:
Comparison of elasticity results for household auto use for major explanatory variables

Explanatory Variable	Schimek (1996)	This Study
R^2 Statistic	0.29	0.33
Household vehicle ownership	0.31	0.43
Household income	0.17	0.15
Household size	0.21	0.21
Household # workers	0.41	0.15
Transit "available"	-0.02	-0.05
Population density	-0.09	n/a*
Auto accessibility	n/a	0.40
Walk accessibility	n/a	-0.0

Note:
* Population density is excluded from this table because the corresponding parameter estimate is not statistically significant.

7. POLICY IMPLICATIONS

The current thinking among many policy makers is that significant reductions in private vehicle use are essential. This study provides some insight on the important question: *Are the linkages between urban form and private vehicle use strong enough that attainable changes in urban form can result in substantial reductions in private vehicle use?* It also provides a range of new ways of viewing and hence understanding the linkages between urban form and private vehicle travel that may help to clarify future policy direction.

First, the study has confirmed that household demographics have a major influence on private vehicle use in a Canadian urban context, particularly household vehicle ownership, income, size and number of employees. In a society where personal wealth is expected to increase over the longer term, the implication is that private vehicle use will also tend to increase.

There is an indication that increases in the extent of working at home act to increase household auto use, through increases in the number of discretionary trips and the share of trips made by auto. Increases in home-based work may bring about shifts in travel patterns, but their effect on total auto use may, in fact, be contrary to expectations.

Second, the study results also suggest that changes in travel accessibility can have a significant impact on private vehicle use. Improved auto accessibility acts to increase private vehicle use, whereas improvements in the accessibilities of the other modes considered (walk, bicycle and transit) act to decrease private vehicle use.

Improvements in walk, bicycle and transit accessibility can be achieved, for existing or new households, by a wide range of measures. A number of these measures are listed below, including various measures not considered explicitly in this study that will nevertheless have some impact on accessibilities. These are included here to provide a broader list from which to consider possible policy actions.

Potential destinations can be located closer to residential areas by:

- increasing the extent of mixed-use developments;
- locating new developments close to potential destinations, for example, through intensification; and
- making the jobs and housing in an area match more closely.

Travel by walking and cycling can be made more attractive by:

- adding streetscaping elements, such as trees along sidewalks;
- developing bicycle trails;
- providing more direct routes, for example, by avoiding curvilinear road patterns; and
- ensuring that street designs are more pedestrian friendly by providing streets that are easy to cross and pedestrian-scaled spaces (e.g., buildings that are close to streets and small parking lots).

Travel can be made safer and more secure by:

- providing improved lighting at transit facilities; and
- reducing auto speeds (e.g., by traffic calming) and narrower roads in new communities.

Travel by transit can be made more attractive, and less time consuming and costly by:

- providing access to more direct routes;
- reducing transit fares;
- providing more direct walking access to transit routes;

- providing more frequent transit service;
- providing better information systems for transit users and making the transit system more understandable for more people; and
- providing transit shelters.

In addition to these measures, reduced auto use and a modal shift from auto to walking, cycling or transit would likely occur if auto accessibilities were reduced, for example, by:

- increasing parking charges;
- increasing gasoline prices; and
- decreasing operating speeds on existing routes.

The results of this study have provided insight into the relative effectiveness of some of these measures to change accessibilities and thus influence auto use. Even those measures found to have relatively little effect on their own may still be included as part of a larger package of measures intended to impact auto use. The intention with this study was to help in the development of appropriate expectations about the relative effectiveness of various specific measures. The ability to change accessibilities in existing built urban areas, where the urban form is already defined, may be more limited than it is in new developments.

Third, the study indicates that the current emphasis on residential density as the element of urban form with the "main" influence on private vehicle use is misplaced. Rather, the emphasis should be placed on increasing transit, walk and bicycle accessibility and decreasing auto accessiblity. Residential density is important only to the extent that it influences travel accessibility by mode and impacts the proportion of travel by auto for compulsory tours. The key is the closeness of destination opportunities to residences, which concerns land-use mix, density and the nature of the transport system connecting these destinations.

Finally, in the modern Canadian urban context, it seems that the provision of a more traditional neighbourhood road layout in new residential developments will, on its own, have a very limited impact on private vehicle use. However, if such traditional neighbourhood design also changes accessibilities, perhaps because it includes more mixed-use developments and attracts households with particular demographic profiles, then such design may indeed lead to different patterns of private vehicle use.

8. CONCLUSIONS

This section offers conclusions about the study results, considering what has been learned about the urban system and household travel behaviour within it as well as methods of studying these relationships.

Summary of Main Findings

Household travel patterns are highly variable.
Much of the variation in auto use is *not* explained by the set of factors considered explicitly here, which includes a wide range of demographic variables, neighbourhood road patterns, density measures and both home and work-based mode-specific accessibilities. The R^2_{adj} values for the various estimation runs did not exceed 0.33. This is expected to be the case because of the tremendous inherent variability in household travel patterns from day to day. The variation in number of compulsory tours is the best explained aspect of household travel out of those considered. Generally, variation in compulsory travel is better explained than variation in discretionary travel.

Demographic variables have the largest influence on auto use.
Of all the different groups of variables examined in this study, the group of household demographic variables has the largest influence on the quantity of auto use with household auto ownership being the largest single influence. The strongest influences on automobile ownership are the number of people in the household and automobile accessibility for the home zone. The latter point indicates that in neighbourhoods with larger distances between activities, free parking and other features associated with high automobile accessibility, households tend to own more automobiles. Household income also strongly influences the rate of household car ownership.

Among the demographic variables, household size, household income, household member roles (related to the household life-cycle position) and number of employed household members have the next largest influences on the quantity of auto use.

Accessibility variables have a strong influence on auto use.
Mode-specific accessibilities (measures that represent the proximity of activities, such as jobs and housing, and the ease and costs of travel between them) have relatively strong influences on household auto use. Accessibilities reflecting conditions in zones containing the homes demonstrated more influence than accessibilities for the zones containing the workplaces of the employed household members.

Accessibility measures capture the complex relationships of several factors including distances between activities (relating to density and land use mix), parking costs, transit fares and road capacity. Making activities physically closer and increasing parking costs results in substantial reductions in VKT. For example, a 50¢ increase in parking costs can result in a 3.4% reduction in VKT. Also by reducing walking times by 10% by making activities closer together, VKT can be reduced by 3.3%.

As auto accessibility at the home location increases (i.e., easier and cheaper to travel by car), households tend to own more automobiles, make larger numbers of more extensive and automobile-intensive discretionary tours and make fewer compulsory tours where these tours are comparatively more extensive and automobile-intensive, with the end result that they tend to make much greater use of autos overall. Auto accessibility at the work location has somewhat similar sorts of influences: as it increases, households tend to make larger numbers of more complex and auto-intensive compulsory tours and tend to use the auto for a greater proportion of travel on discretionary tours.

As walk accessibility at the home location increases, households tend to own fewer autos and make larger numbers of tours that are less extensive and less auto-intensive, with the end result that they tend to make less use of their autos overall. As walk accessibilities at work locations increase, households tend to make slightly shorter, more complex compulsory tours and much less auto use, while the number of compulsory tours is largely unaffected. It seems reasonable to expect that bicycle accessibilities would have broadly similar influences, but that strong correlations between walk and bicycle accessibilities within the data made it difficult to discern their separate influences.

The influence of accessibilities on auto use is greater than the influence of density on its own.
Population and employment density variables can appear to have statistically significant and even substantial influences in regression equations concerning auto use when other variables, such as household income, which are correlated to density, are excluded. The apparent influence of density largely disappears when other correlated variables, in particular, mode-specific accessibilities, are included in the equations.

It is more appropriate to use mode-specific accessibilities than densities in such regression equations, since they capture the complex interplay between a wide range of factors, including proximity of activities. While density is a factor in the proximity of activities, it should be considered in combination with land use mix and other accessibility factors. For example, densely populated neighbourhoods would be associated with increased auto accessibility and auto use if they contained no shops, jobs or other non-residential destinations, free parking, poor transit service and high road capacity. Auto use would also be affected by household income, size and other demographic variables.

Road patterns have a minor influence on auto use.
Neighbourhood road patterns have relatively minor, but consistent, influences on household auto use. More regular, rectangular street patterns tend to be associated with a slightly reduced auto use. But it would appear that these effects are much smaller than is implied in the literature.

Different indicator variables provide different indications.
In addition to auto use and ownership, a variety of aspects of household travel were considered, including number of tours, trips per tour, distance per trip and proportion of travel by auto. The effects of certain factors on these different aspects were sometimes found to differ widely from their influences on auto use overall. For example, household size has a strong positive influence on auto use overall, but also acts to reduce the proportion of all travel by auto. These results and the indications they provide are not contradictory, rather they help in the development of a more complete understanding of the nature of the influence of different factors on household travel patterns and on the nature of household travel overall. Such differences regarding the components of household travel may go a long way to help explain why studies considering different forms of indicator variables have obtained apparently contradictory indications of the influences of specific explanatory variables.

Access to transit has a minor influence on auto use.
As transit accessibility at the home location increases, households tend to own slightly fewer automobiles and make larger numbers of less extensive compulsory tours, with the end result that they tend to make somewhat less use of autos overall. Consistent with this, households located in zones without transit services tend to own more cars, make fewer, more complex and auto-intensive tours, with the end result that they also tend to make more use of autos overall.

Summary of Policy Implications of Findings

While this study shows that automobile use is largely influenced by factors beyond the 'reach' of planners and engineers, it also indicates that measures that improve walk, transit and bike accessibility and that reduce auto-accessibility can result in substantial reductions in household

automobile use. The influence is greatest when these measures are applied in combination. Such measures include:

- reducing walk time by locating activities closer together, which could be achieved through intensification and mixed-use development;
- increasing parking charges and gas prices to increase the money costs for auto use;
- making walking and bicycling routings more direct in order to reduce walking and cycling times;
- ensuring that street designs are more pedestrian friendly by providing attractive streetscaping, bus shelters, streets that are easy to cross and pedestrian-scaled spaces (e.g., buildings that are close to streets and small parking lots);
- introducing measures to slow down autos, such as traffic calming on existing streets, designing narrower roads in new communities;
- encouraging regular rectilinear street patterns over curvilinear patterns;
- reducing bus fares; and
- introducing bus priority measures to reduce bus running times, in particular where there is a corresponding increase in auto travel times.

Of the measures that were considered in this study, decreases in walking times would be the most effective, followed by increases in auto riding times, all other things being equal. Increases in parking money costs would also appear to be comparatively effective, although the analysis does not allow a direct comparison. Several such measures applied in combination can be expected to have an additive effect.

The introduction of more rectangular and regular neighbourhood road patterns can be expected to bring about only relatively small decreases in household auto use overall. Certainly, such treatments should not be relied on, on their own, to bring about any substantial changes.

Increases in density, particularly over a relatively larger area, can be expected to reduce auto use in as much as they act to increase non-auto accessibilities. That is, density, when combined with mixed-use and other accessibility factors, affects auto use by allowing activities to be closer together and more accessible by walking, transit and biking, thus reducing VKT. Increases in density at the neighbourhood level will also act "directly" to bring about small decreases in the proportion of auto use for compulsory travel, again all other things being equal. But this will not be enough to impact auto use overall beyond the effects acting via accessibilities. Rather than implementing policies to increase densities in isolation, it would be far more effective to implement a package of measures that increased non-auto accessibilities and decreased auto accessibilities, including mixing residential and non-residential activities, increasing parking, reducing road capacities, etc.

Potential Limitations

The accessibility measures considered in this study may not provide a complete representation of the proximity of all relevant destinations influencing household travel patterns. To achieve this, inter-city observations would have to have been included, which was not possible in this study given the reliance on data from just Edmonton. Nevertheless, for indications that are useful with respect to policy implications, it is much more appropriate to consider the impacts of measures at the neighbourhood level.

The inclusion of weekend trips, in the survey data would have provided a more complete representation of travel behaviour, particularly for discretionary trips. However, only data for a single weekday were available.

The results depend on the unique conditions of Edmonton. There are differences between Edmonton and other Canadian cities that may affect the degree of transferability of the results.

- Many new suburban neighbourhoods in Edmonton have a relatively high population density of over 30 people per hectare, which is higher than densities typical of the suburbs of other Canadian cities (Raad and Kenworthy, 1998).

- Edmonton enjoys relatively low levels of traffic congestion. As a result, the 10 per cent reductions in road capacity considered in the sensitivity analysis had relatively little impact on travel times and thus on accessibilities.

However, a comparison of Edmonton characteristics with those of other Canadian cities, including transit service, transit ridership, percentage of workers walking and cycling, overall urban density and proportion of jobs in CBD indicates that, generally, Edmonton is a fairly typical Canadian city. These statistics reveal that it has much more in common with Canadian cities than with American cities (Raad and Kenworthy, 1998).

A further limitation is the lack of inclusion of some of the more qualitative aspects of urban form that might affect travellers' decisions to walk, cycle or take the bus. For example, intuitively, walking and cycling (reasonable distances) are more likely if the aesthetic experience includes elements such as trees, wide sidewalks, attractive architectural detailing and a human scale.

This study did not consider the full range of effects that traffic calming measures implemented on more than collector roads might have on auto use. This study was limited to consideration of just the effects of some of the capacity and speed changes that could result from traffic calming. In particular, it did not address the reductions in auto use that might arise because traffic calming, with the introduction of winding, narrower lanes and additional stops, makes driving more difficult and slower. This suggests that the effects of traffic calming would be greater than the fairly modest effects of speed and capacity reductions obtained here, but exactly how much greater is uncertain. It could still be indicated that the overall effect on auto use would be rather small. Further work is required before any strong conclusions are drawn.

It is important to remember that the results obtained in this study do not indicate the causal direction of the identified relationships between elements of urban form and components of household travel generally and car use specifically. That is, the results indicate that either:

- households in locations with specific conditions tend to behave in response to those conditions;
- households that tend to behave in certain ways also tend to select locations with specific conditions; or
- some mix of both of the above options.

It is important to appreciate, from a policy perspective, that in the strictest sense these results do not indicate that changes in elements of urban form will necessarily lead to changes in household travel behaviour. It certainly seems likely that this would be the case, and many of the discussions of findings and policy implications in this report are structured to be consistent with that assumption. But the data set used in this study is cross-sectional, for a single point in time, and a panel data set indicating changes through time would be required in order to provide such indications independent of that assumption.

Appropriate Directions for Future Work

There are four main areas where additional work is required to help researchers and policy makers in Canada gain a fuller understanding of the overall influence of urban form on private vehicle use overall.

- In the strictest sense, the results obtained in this study concern households in just the Edmonton region. It would be appropriate to conduct similar studies for other urban areas in Canada, to see if similar results are found, and to allow urban-area wide-density measures to be considered in addition to the neighbourhood-level home and work measures considered in this study. However, as indicated above, a comparison of transit usage and other characteristics indicates that Edmonton is more typical of a Canadian city than a United States city.

- The results concern travel patterns in October and November, representative of Canadian

late fall and early winter conditions. Over the month of November during the survey, the mean temperature in Edmonton was -4.6°C, with average daily temperatures between -0.1°C and -9.1°C. Thus, travel by walking and cycling would be lower than it would be in warmer weather. It would be appropriate to repeat the analysis using data collected in the summer.

- This study examined household travel data for a single weekday. This single weekday analysis has limitations: there is significant variation in travel from one weekday to the next and weekend travel is completely missed. However, comprehensive household travel survey data are expensive to obtain and few households may be willing to participate given the effort required.

- This study has considered the use of mode-specific accessibilities in the description and quantification of aspects of urban form. More research is required to determine the magnitude of impacts of alternative urban form policies on mode-specific accessibilities and, hence, concerning the magnitude of their potential impacts on private vehicle use.

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ENDNOTES

1 The selection of an appropriate measure of density is problematic when considering developing areas of a city. If only part of a new neighbourhood has been constructed, and undeveloped greenfields are interspersed with areas of completed construction, then the calculated development density for the neighbourhood is low if the greenfields areas are included (for a larger area density) and much higher if only the areas of completed construction are included (for a micro area density or an approximation of the density at the ultimate build-out of the area). It is not apparent a priori which is more appropriate to use in an analysis of the influences on automobile use in such cases—the lower larger area value or the higher micro area value—so both are included in this study.

2 Various person-type and employment-type variables, such as HSHHS and HNGSC for number of senior high school students and number of grade school students respectively, are used in combination with a variable for household size. This facilitates a representation of the mix of ages and employment status in the household and thus of the life cycle stage of the household along with the size of the household.

3 The values shown for parking cost increases of $0.50 are not directly comparable units of change. They differ from the other variables in that they are absolute (0.50) versus relative (10 per cent), as discussed below.

4 When all three mode "in" times were reduced simultaneously, the elasticities were able to pick up shifts from one mode to another. For example, when activity destinations are moved closer together, walking and transit become more viable and attractive, thereby resulting in less auto use. However, when auto "in" times are reduced and all other parameters held constant, the modal shift to walking and transit cannot be accounted for, therefore auto use tends to increase.